Capabilities and Challenges in CFD: A Perspective from the DoD HPCMP CREATE™-AV Kestrel Development Team

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DOD HPC MODERNIZATION PROGRAM

Presented by Dr. David R. McDaniel

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Overview

- Introduction
- Kestrel overview
- Snapshot of Kestrel production capabilities
- Challenges and future directions
- Summary

Introduction

DoD HPCMP CREATE™– AV Kestrel

Kestrel is the fixed-wing product of the CREATE™-AV program

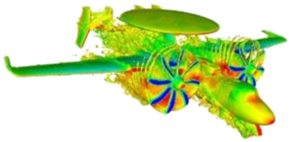
- Born from requirements gathered in 2007/8 to address modeling & simulation deficiencies in the DoD acquisition process
- Multi-mesh/multi-solver paradigm
  - Unstructured near-body
  - High order Cartesian off-body
  - Adaptive Mesh Refinement
  - Fast overset connectivity
- Full spectrum of aircraft type
  - Fighter, Bomber, Tanker, Transport, UAV
- Full spectrum of flight conditions/missions
  - Low-speed, transonic, supersonic
  - Cruise, maneuver, take-off/land, refueling, formation flight, store carriage and release, pilot ejection, precision air-drop, and more…

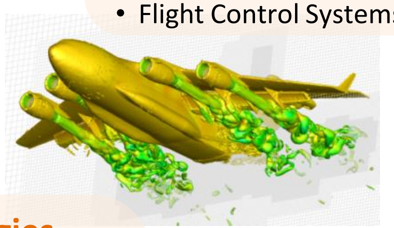
Kestrel Version 7

Capabilities

High fidelity coupled physics

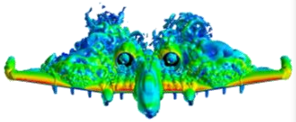
- Aerodynamics
- Structural Dynamics
- Propulsion
- Flight Control Systems

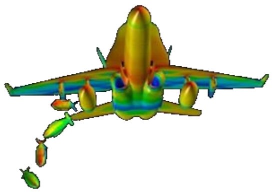




Key Technologies

- Multi-mesh paradigm
- Adaptive mesh refinement
- High order Cartesian solver
- Python-based common software infrastructure
- Generalized interface for externally developed "plug-in" capability modules





Expanding Footprint of Kestrel Adoption

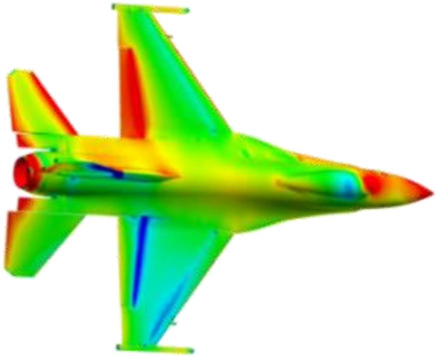
- Over 500 active license holders (as of May 2017)
- 21 Defense Orgs (Labs, Engineering and Test Centers) actively using Kestrel
- All major manufacturers actively evaluating Kestrel
- 5 Orgs affiliated with Other Federal Agencies using Kestrel to support US Gov't Programs
- Several select US Academic Institutions and the Service Academies using Kestrel to support DoD Programs

Introduction

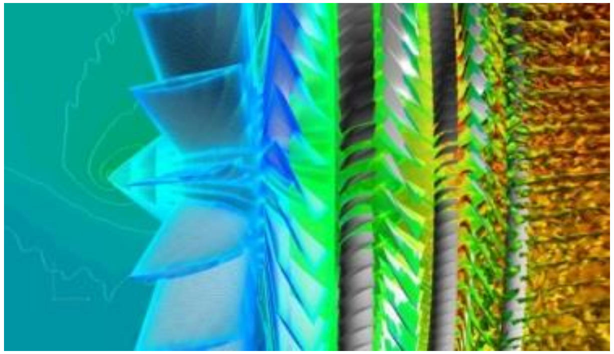
- **Many cost/performance issues in DoD aircraft acquisitions may be traced back to inadequate modeling of multidisciplinary phenomena**
  - …or maybe the "operational application" of the physics capabilities
- **Kestrel:**
  - Provide a <u>production</u> multidisciplinary capability for DoD acquisition personnel
  - Plan for the change → "manage the chaos"
  - Usability, robustness, efficiency, and accuracy are all competing factors

Kestrel Overview

Kestrel Architecture



- **Kestrel User Interface (KUI/Carpenter)**
  - Pre-processing
    - Job setup and validation
    - Mesh manipulation
  - Post-processing
    - Tracking file plotting and manipulation
    - Reduced-order model building

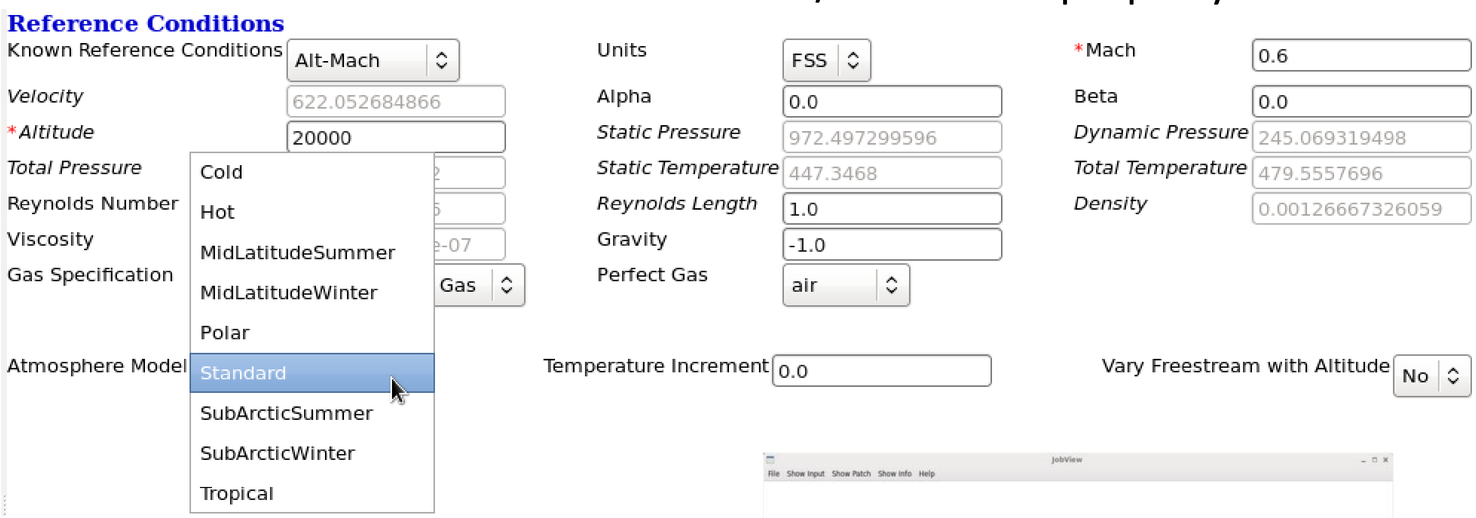


- **Kestrel Run Time Execution Software**
  - Common Scalable Infrastructure (CSI)
    - Unique event-driven infrastructure
    - Homogenous behavior in the infrastructure, physics capability in components
    - Data Warehouse – generic data definition and automatic language translation
  - Modular Components
    - Elemental physics capabilities → large degree of use case flexibility
    - Testable code units → may be modified/replaced with confidence
    - Written in Python/C/C++/FORTRAN

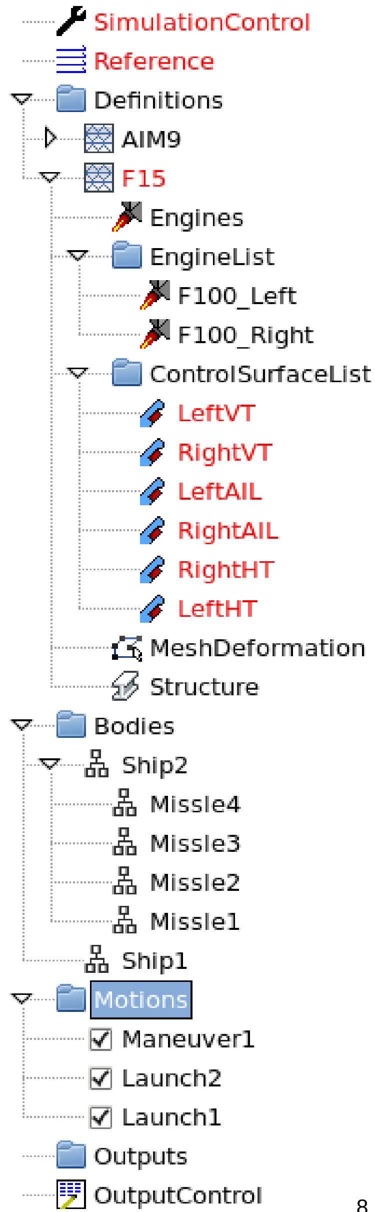
Job Setup and Input Validation

- **Tension between making the hard job easy to set up and making the easy job hard to setup**

Automatic unit conversions and reference/freestream property calculations

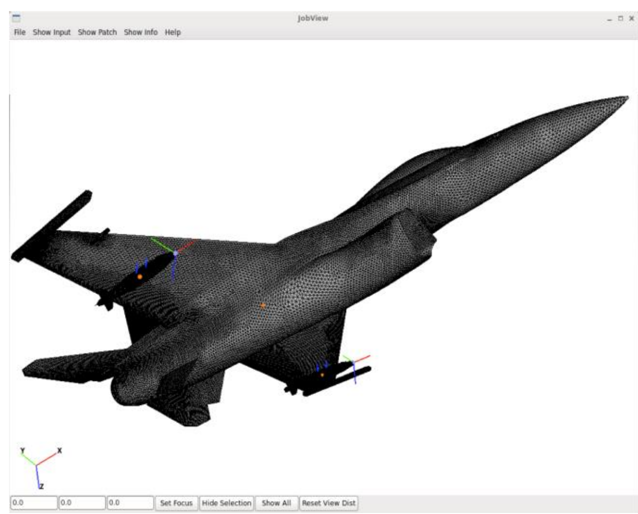


Entity-driven setup

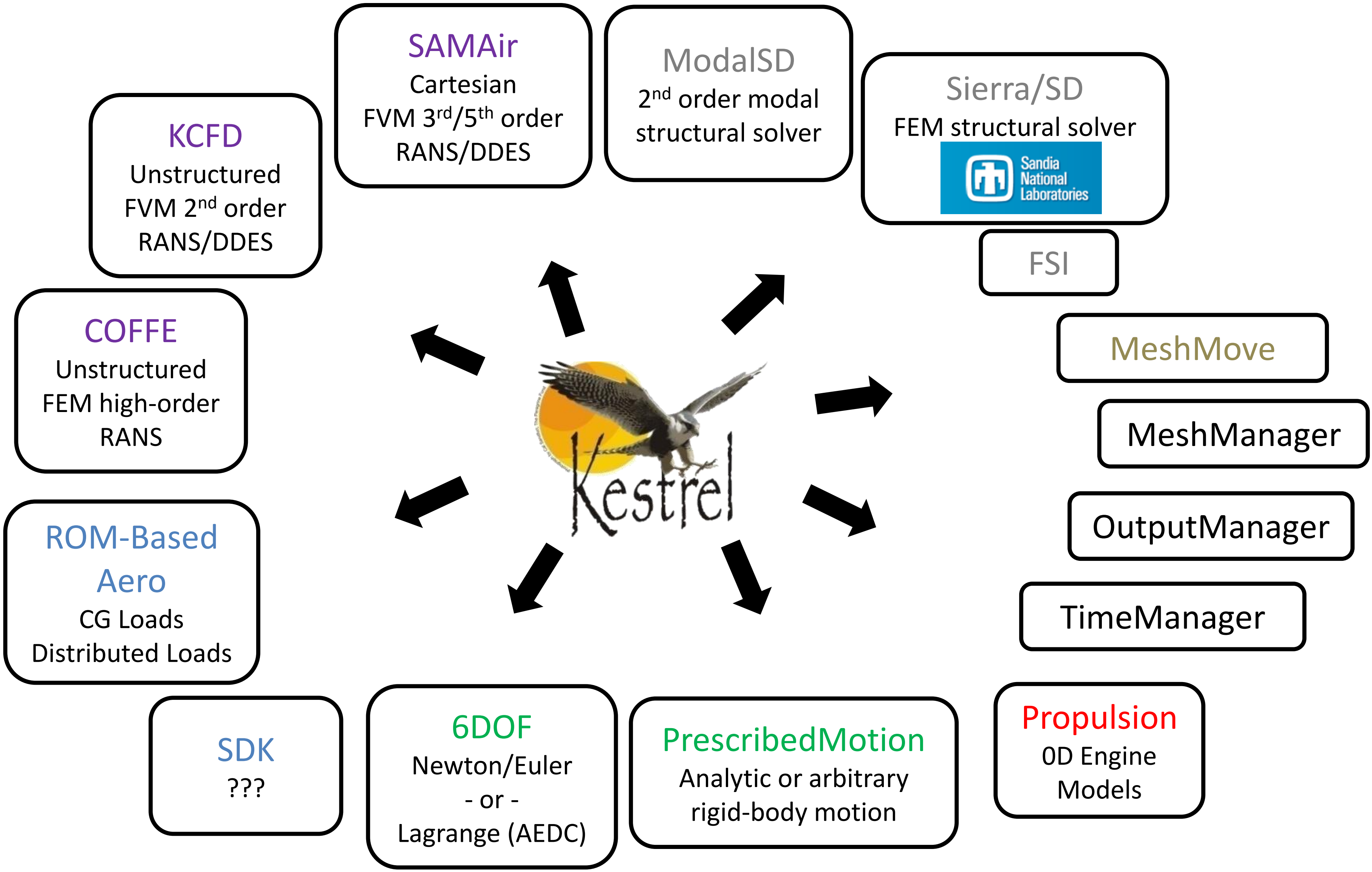


Jobview:

- Visual validation of complex job setup
- Assembled body positions
- Unit conversions/scaling
- Position-dependent input locations
- Boundary conditions



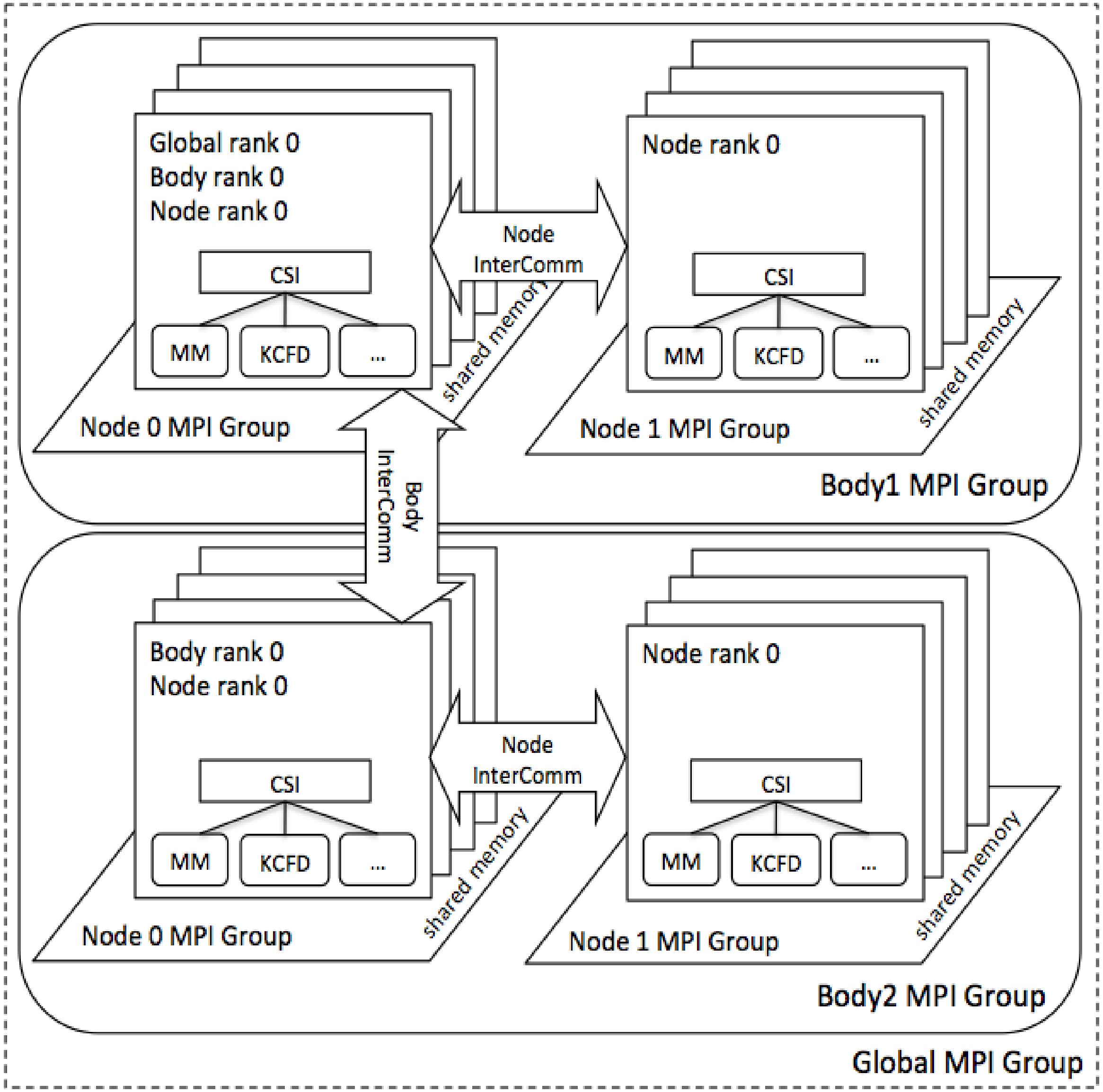
Modular Components



- **Nothing prohibits use of derived or empirical models**

Parallelism

- **Hierarchy of MPI communicators**
- **Shared memory for duplicate data**
- **1 body per process**

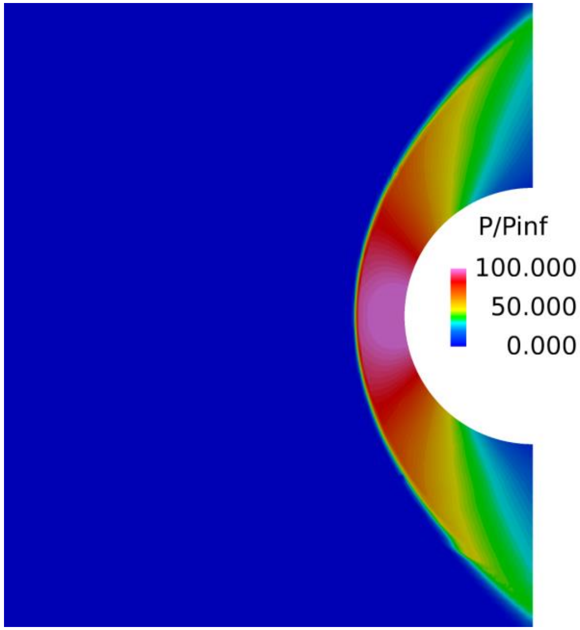


Testing and Validation

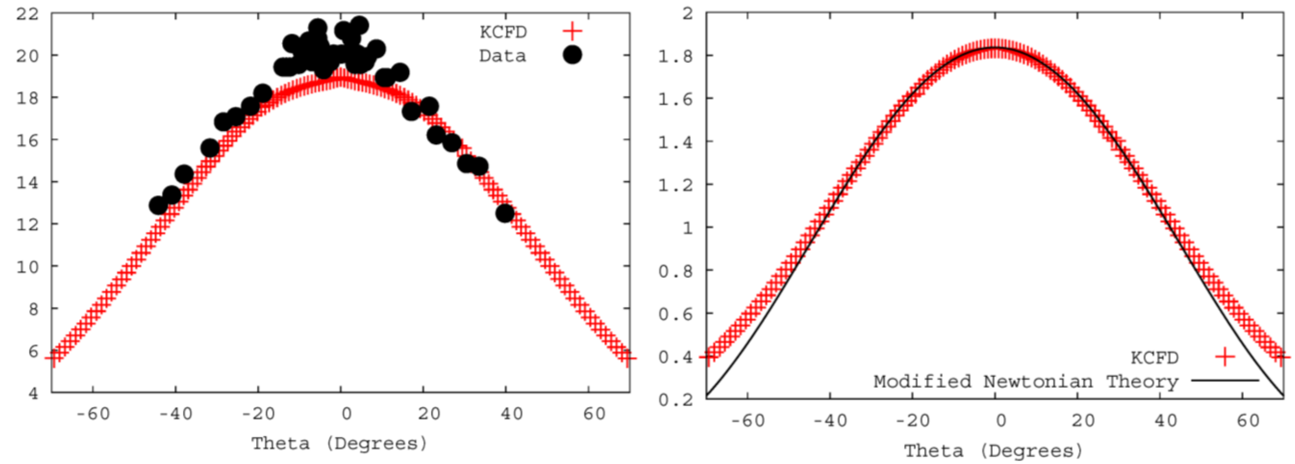
- Continuous testing model is vital to Kestrel process
- Boldness and confidence to undertake substantial changes to software
- ~3500 unit, ~250 integration, ~25 system tests each night (~17k assertions)
- Automatic Testing System executed every 2 weeks and covers a large range of use cases and flow regimes (~125 separate jobs)

Kestrel Capabilities Snapshot

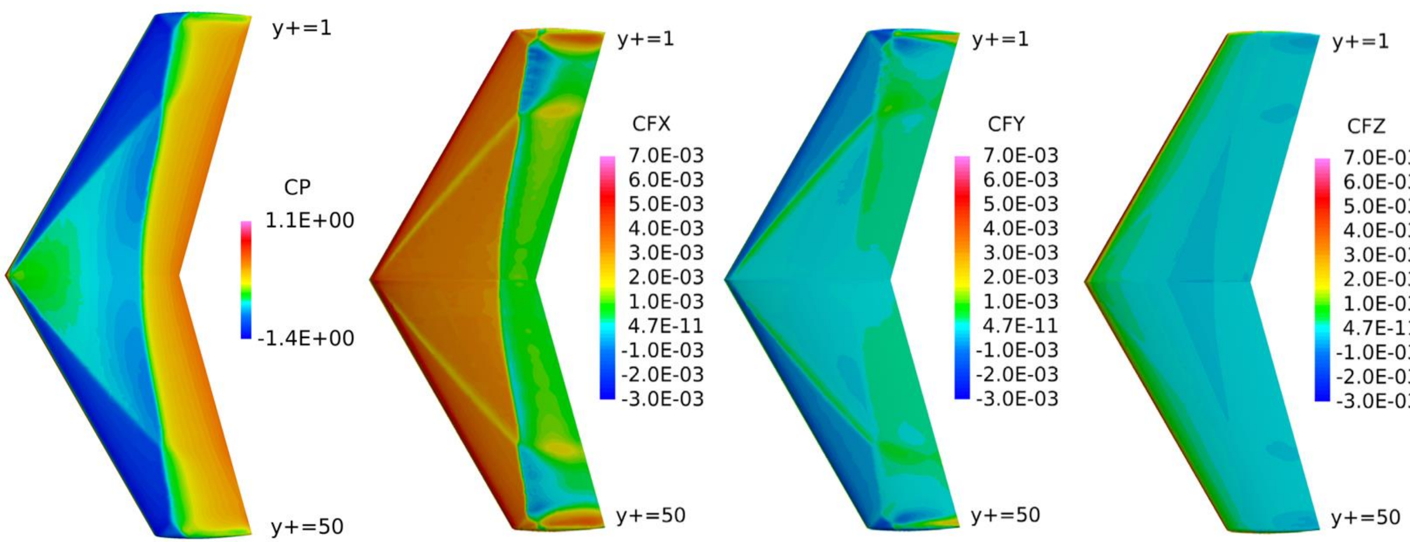
Flow Solver Performance



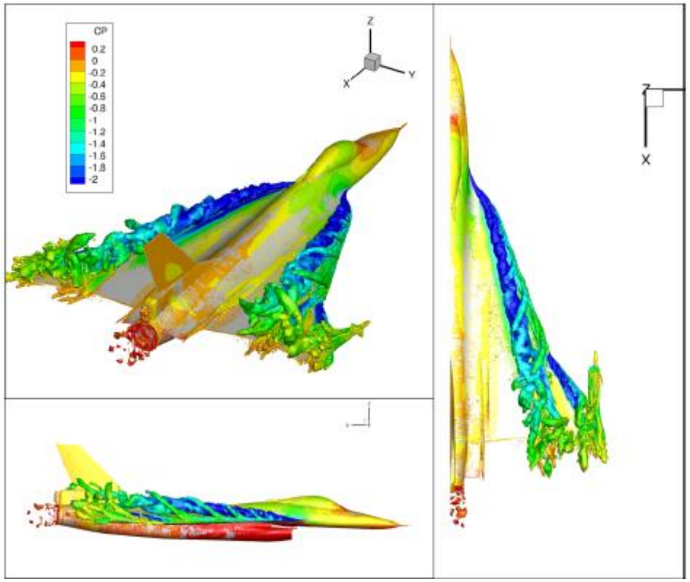
Holden Cylinder - Mach 16.01



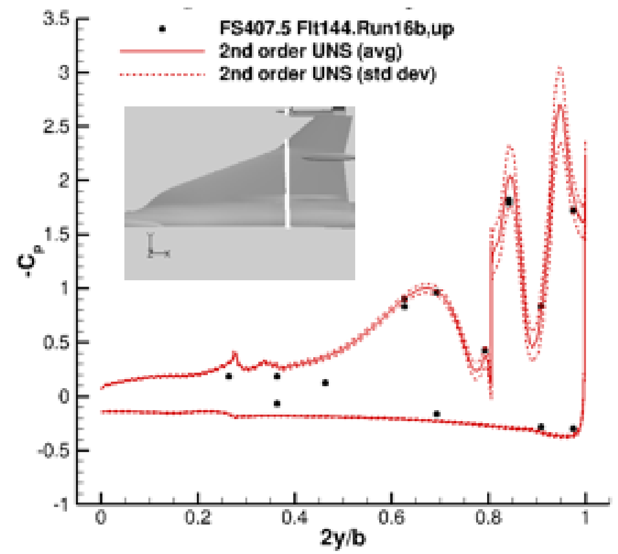
ONERA M6
0.84 Mach
5.06° AOA
Baseline Menter
w/ wall functions



Flow Solver Performance

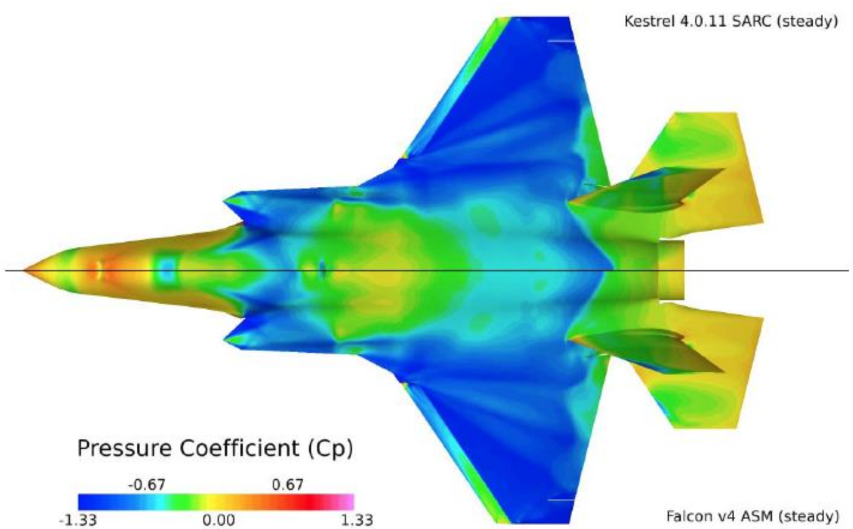


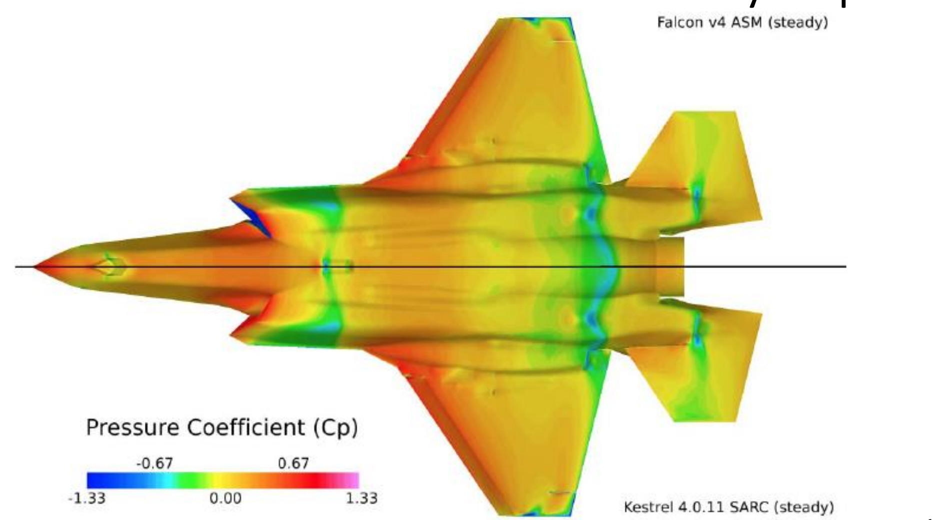
F-16XL Unsteady Solution
20° AOA
SA-DDES
M=0.242, 10k ft
(AIAA 2015-2873)



Transonic F-35 @ 14 deg AOA (AIAA 2015-0551)

- No special initializations
- Performance and scalability on par



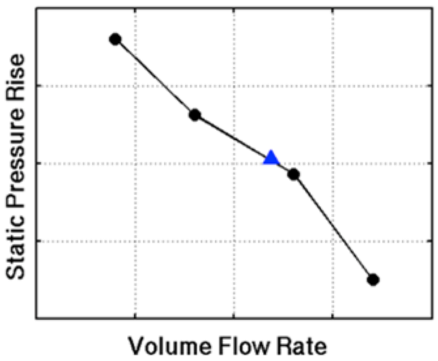


Propulsion Integration

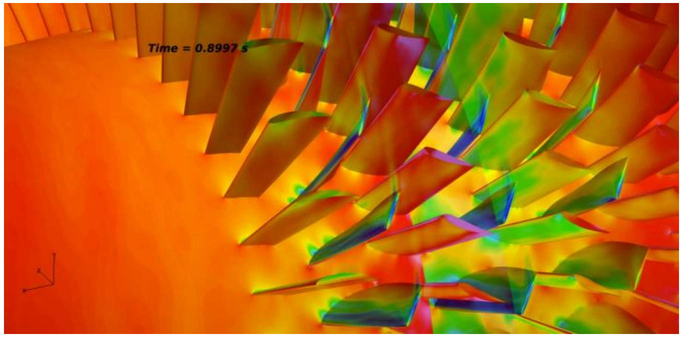
F-16
0.6 Mach
20k feet
6 deg AOA
F110-100 0D transient engine model

30° PLA

85° PLA

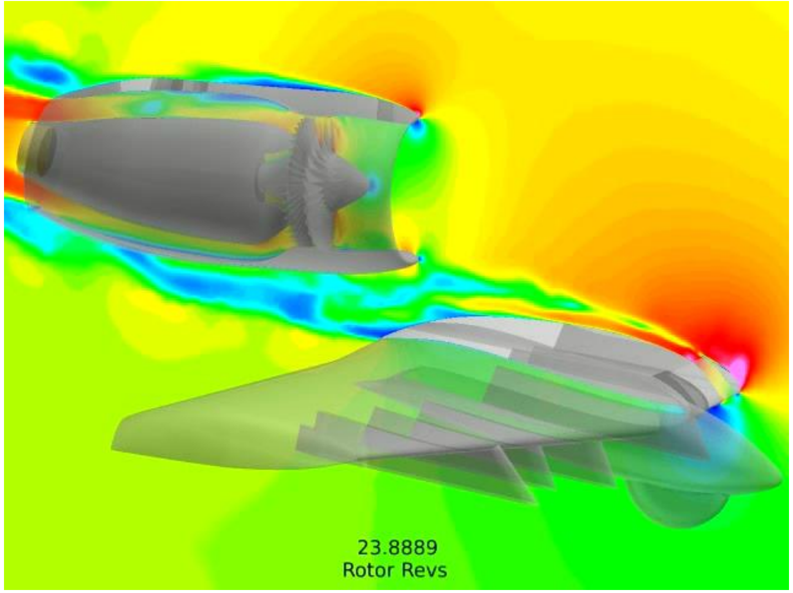


C1 Compressor
AEDC 16T
8 blade rows
333 blades



A-10 Inlet Distortion
21° AOA

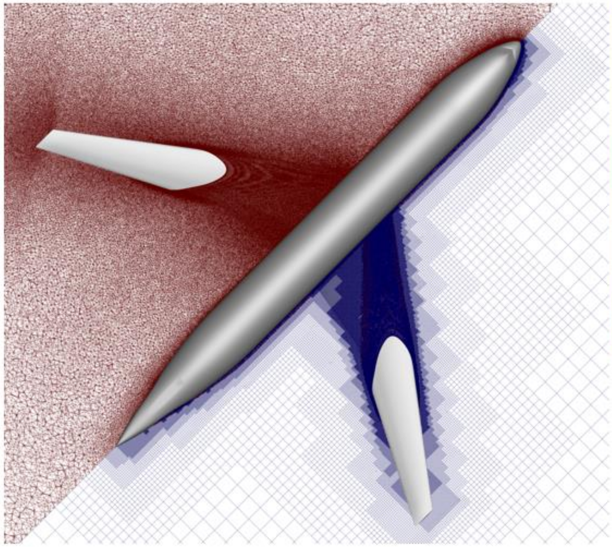
Full annulus TF34 fan stage w/ static BC core flow

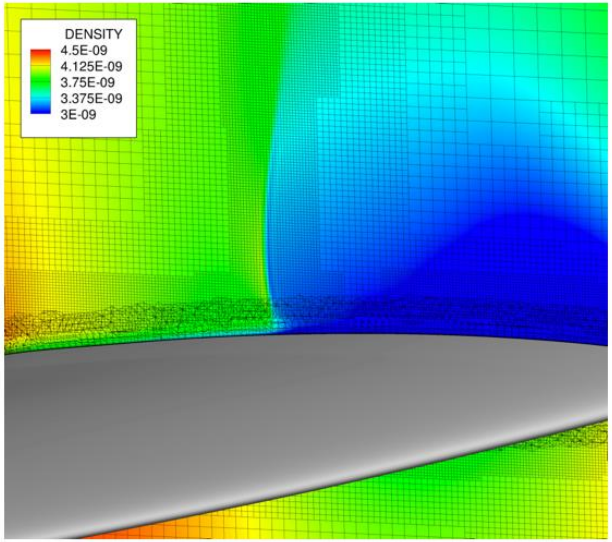


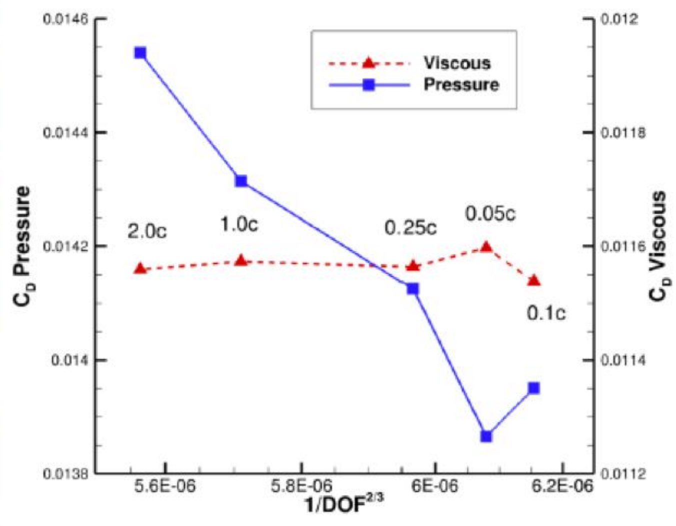
Near-body/Off-body Solution Capability

- Off-body Cartesian solver supports high order and adaptive mesh refinement
- Near-body unstructured solution coupled via overset

NASA CRM (DPW)
Mach 0.85
$C_L = 0.5$



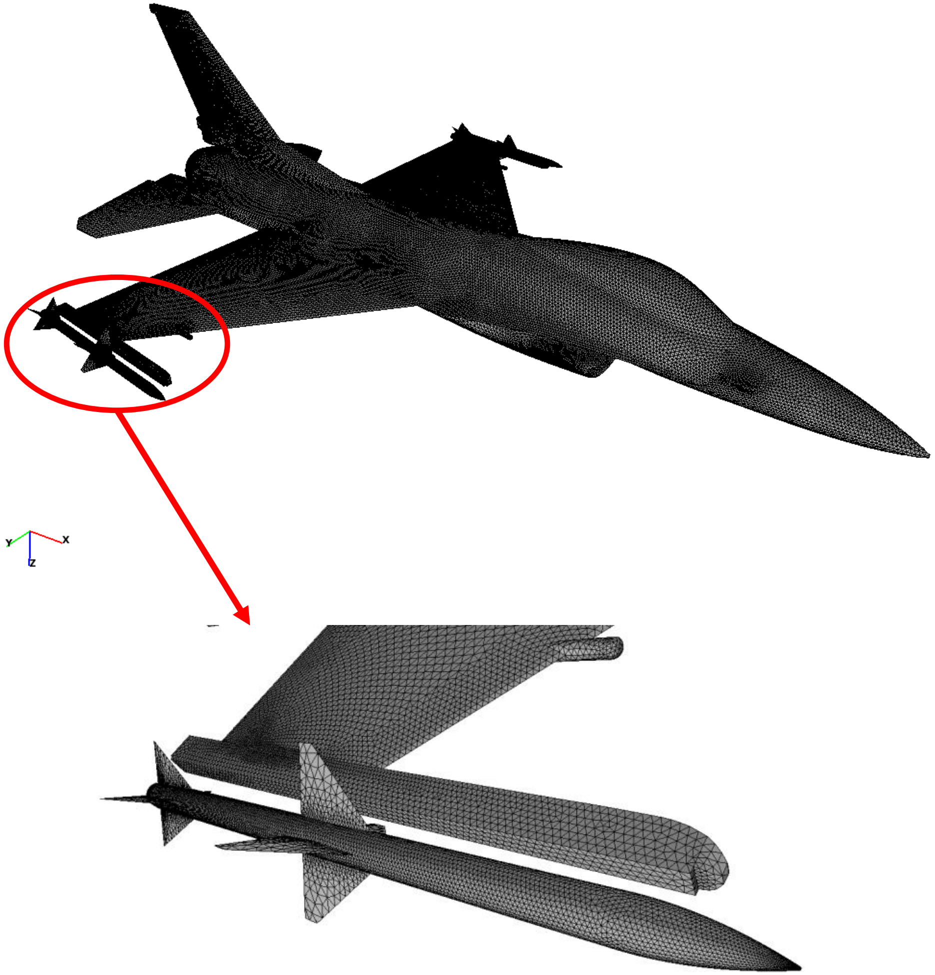


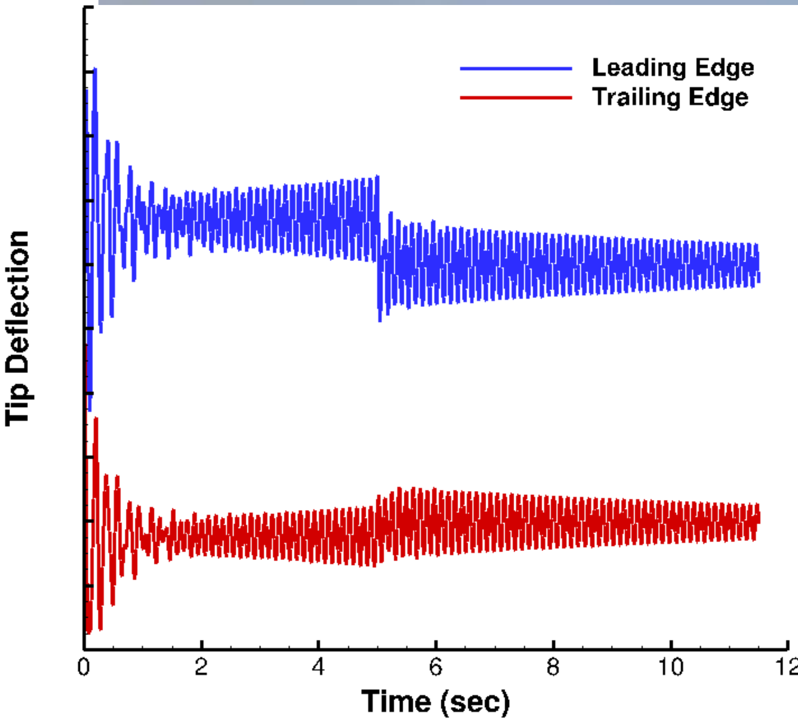


Eymann & Nichols, Thurs @ 1400 in Tower Court B, 336-CFD-30 (AIAA 2017-4292)

Multi-body Elastic Effects

Notional Sidewinder Release from Elastic F-16
Mach 0.9, Sea Level, SA+DDES

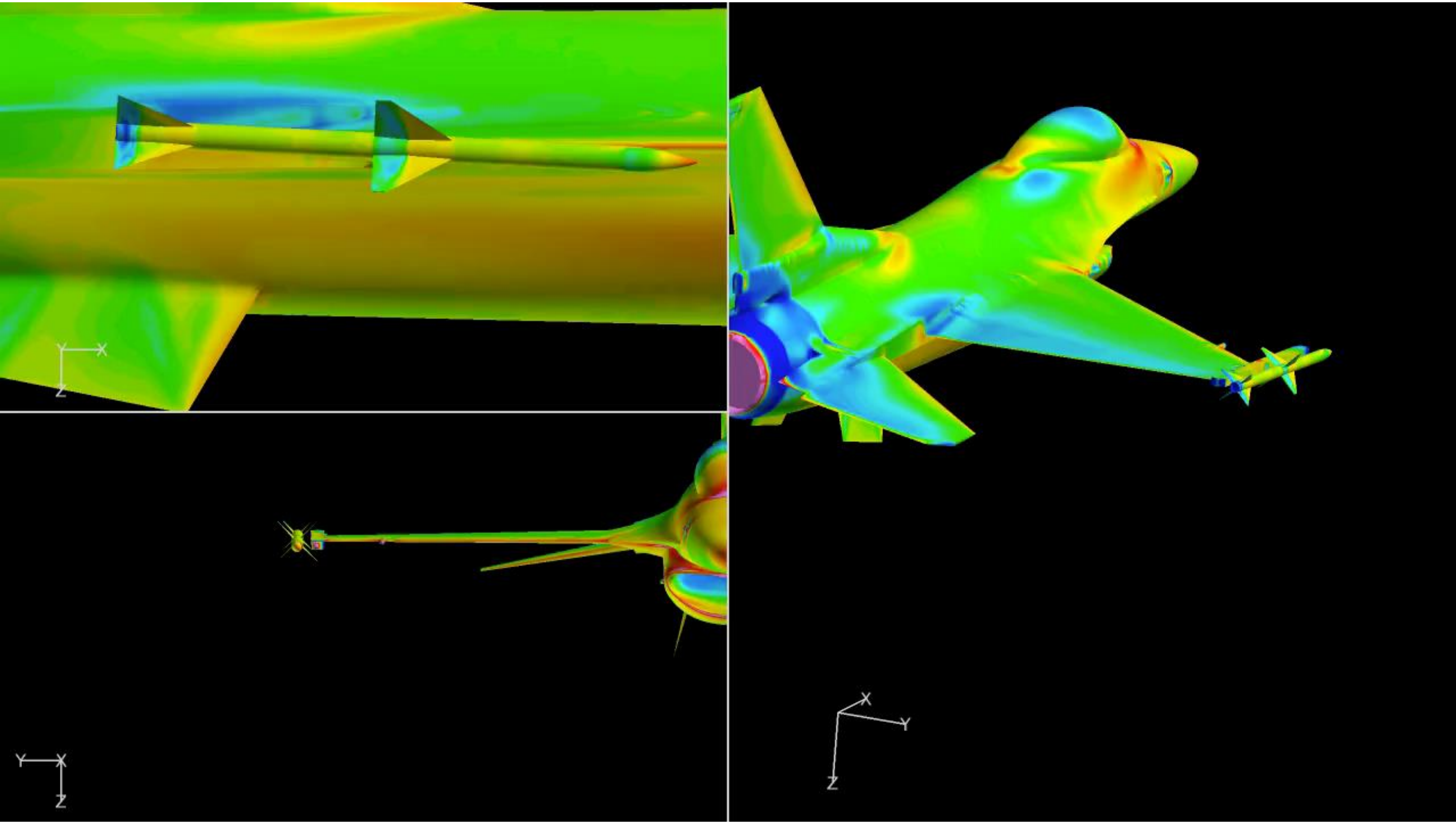




Multi-body Elastic Effects

Notional Sidewinder Ejection from Elastic F-16

Mach 0.9, Sea Level, SA+DDES



Challenges and Future Directions

Challenges and Future Directions

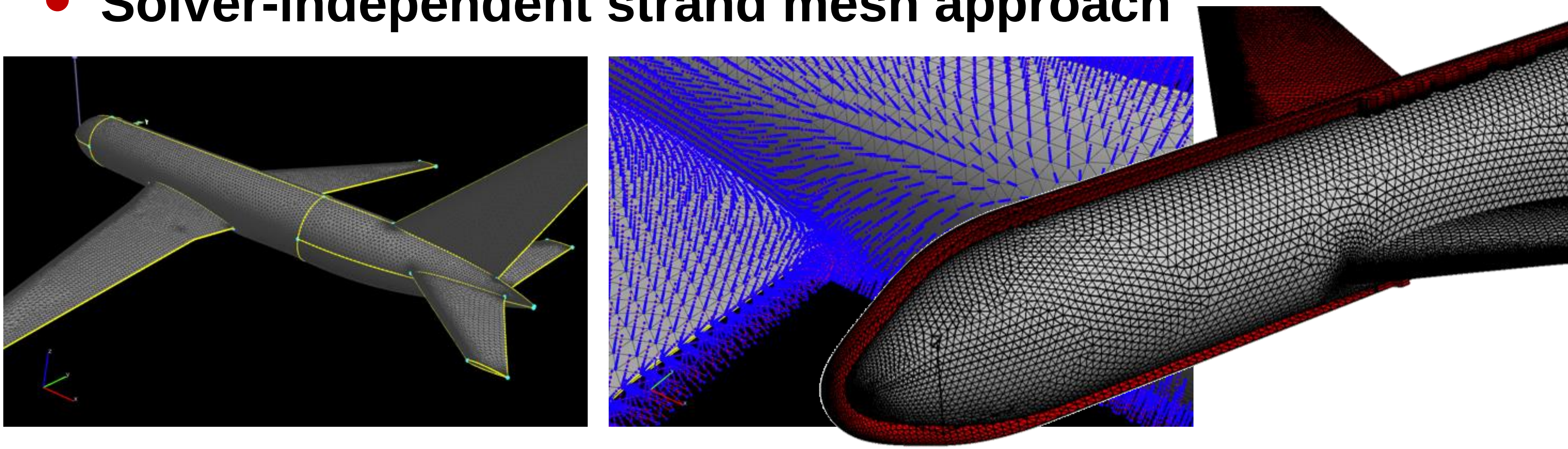
- **Kestrel → robust and maintainable simulation capability must be balanced with accuracy requirements**
- **Productionizing high-fidelity physics capabilities while…**
  - Minimizing code complexity (small code base)
  - Adapting to future algorithm advancements
  - Adapting to future hardware changes
  - Supporting proprietary / custom applications
- **Mention of ongoing Kestrel development activities in the context of these next topics should not be construed as the ideal end-state solution**

Multiple Everything

- **Necessary to model multiple disciplines at multiple time scales to capture target physics**
- **Flow regimes of interest moving to opposite ends of the speed spectrum**
  - UAV → incompressible, highly-flexible
  - Hypersonics → transition, chemistry, heating
- **Unsteady, time-accurate simulations**
  - Example: Full-annulus multistage compressor
    - Billions of grid points required for 0.5% mass flow, 2% total property convergence
    - Time step restricted by rotation rate (on the order of 10^4 RPM)
    - Pressure waves must transit the distance between inflow/outflow several times
    - Throttle transients and aircraft maneuvers have time scales of seconds
- **Multiple gas species and chemistry effects**
  - Efficient perfect gas vs. multiple reacting species and inflow specifications
  - Support for custom thermodynamics/chemistry models

Mesh Generation and Refinement

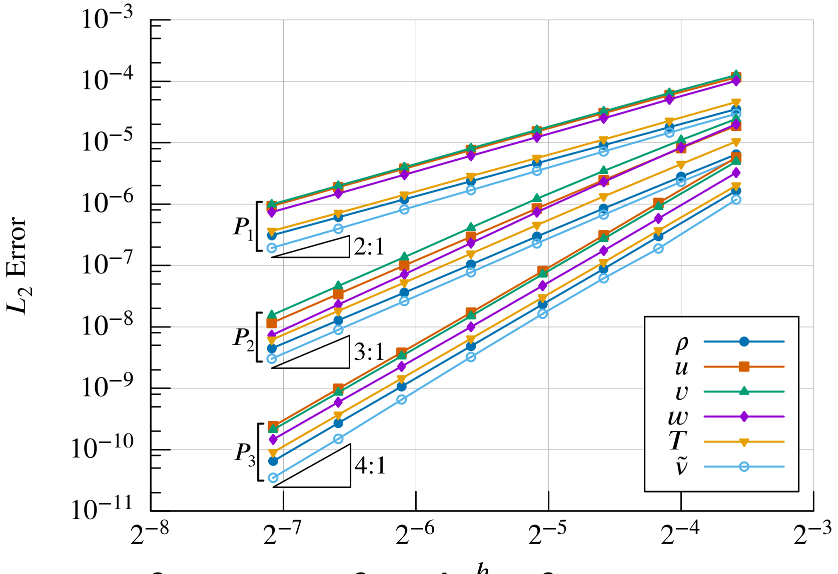
- **Need for *effective* automatic meshing process for general configurations**
  - 1st Geometry and Mesh Generation Workshop at AVIATION 2017
- **Solver-independent strand mesh approach**



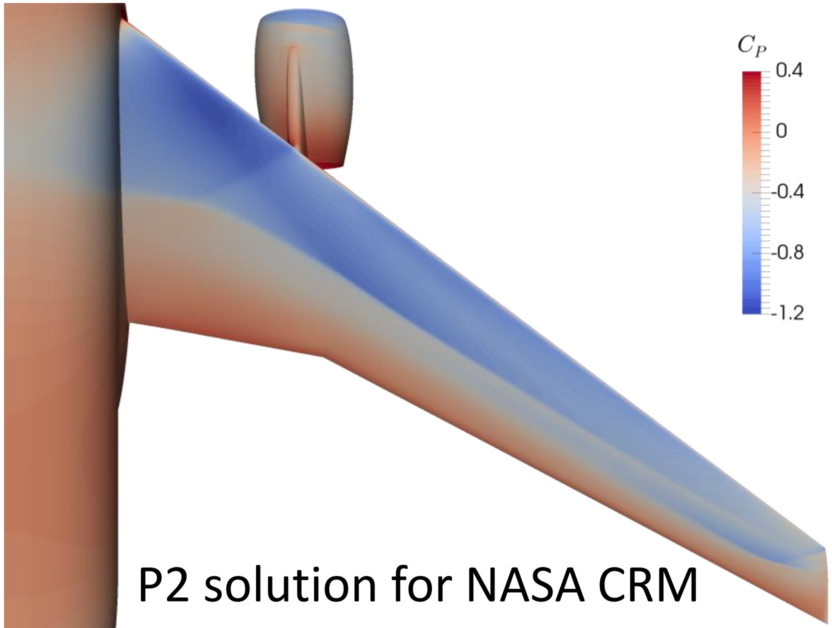
- **Standardized methods for determining *when and where* adaptive mesh refinement should occur**
- **Access to underlying geometry for constrained surface mesh movement (CREATE Capstone SDK)**

High-Order (Unstructured) Solutions

- **Some use cases are out of reach of 2nd order solvers**
  – Scalability/memory restricts continued refinement of the mesh
  – Numerical dissipation prevents needed level of solution convergence
- **High-order overset can be problematic**
- **Mesh generation/visualization (tools AND training)**
- **Kestrel/COFFE**
  – SU/PG FEM, strong convergence, path to high-order, adjoint consistent



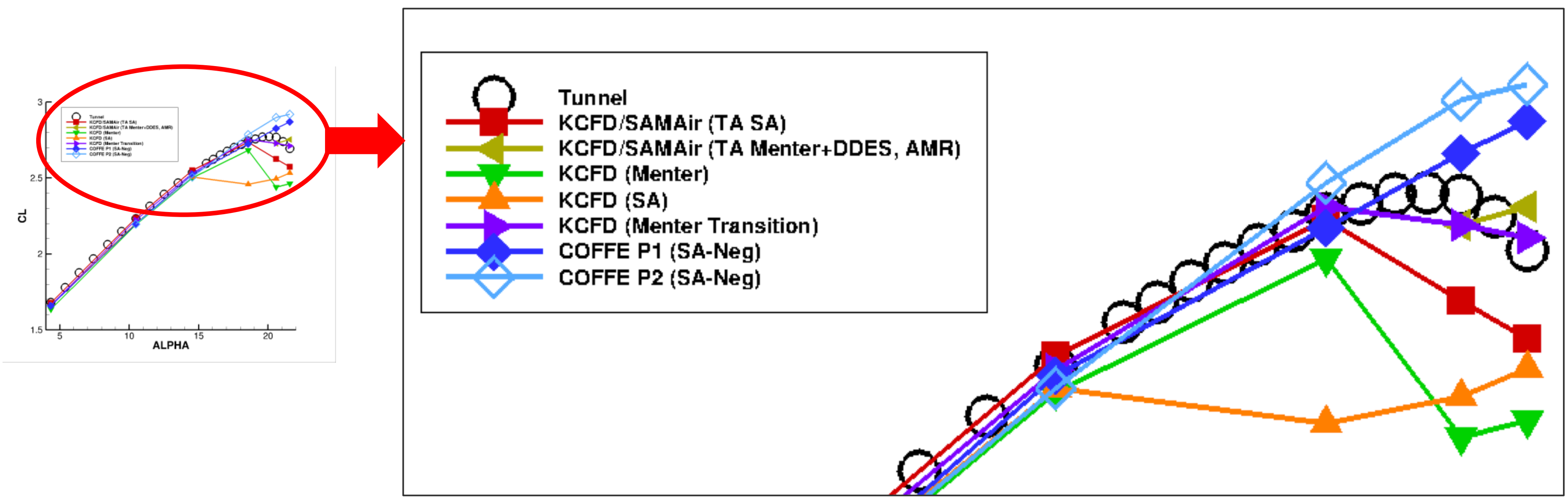
Verification of order of accuracy



P2 solution for NASA CRM

(High Lift) Turbulence & Transition

- **Accurate solutions near/beyond stall are necessary**
  - New high-performance aircraft being designed to operate close to stall
  - Turbomachinery blades typically operate near stall
- **Transition modeling is key in production environment**
  - Transport-equation-type models are a necessity
  - Requirement in hypersonic flows

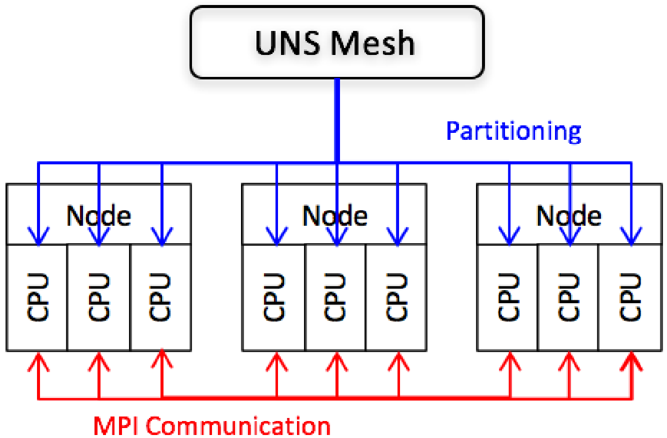


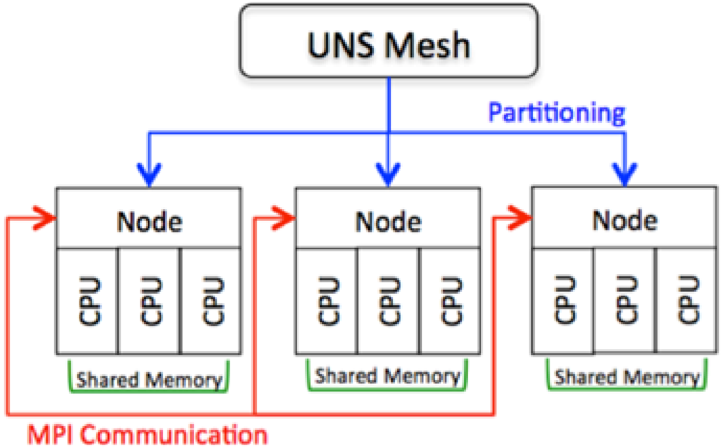
JAXA Standard Model, Mach 0.172

3rd AIAA Hi-Lift Prediction Workshop (AVIATION 2017)

Solution Parallelism

- **Shared memory compute architectures are dominating**
  - Knights Landing processors entering production in DoD HPCMP this summer
- **Coarse-grain, hybrid parallelization approaches critical to future scalability**
- **Kestrel shared memory requirements**
  - Low overhead with minimal code complexity (maximum portability)
  - Compatible with persistent data accessible across multiple languages
- **Potential cache issues with large mesh partitions**
- **Look at other parallelism avenues (time, discipline, etc.)**





Solution Parallelism

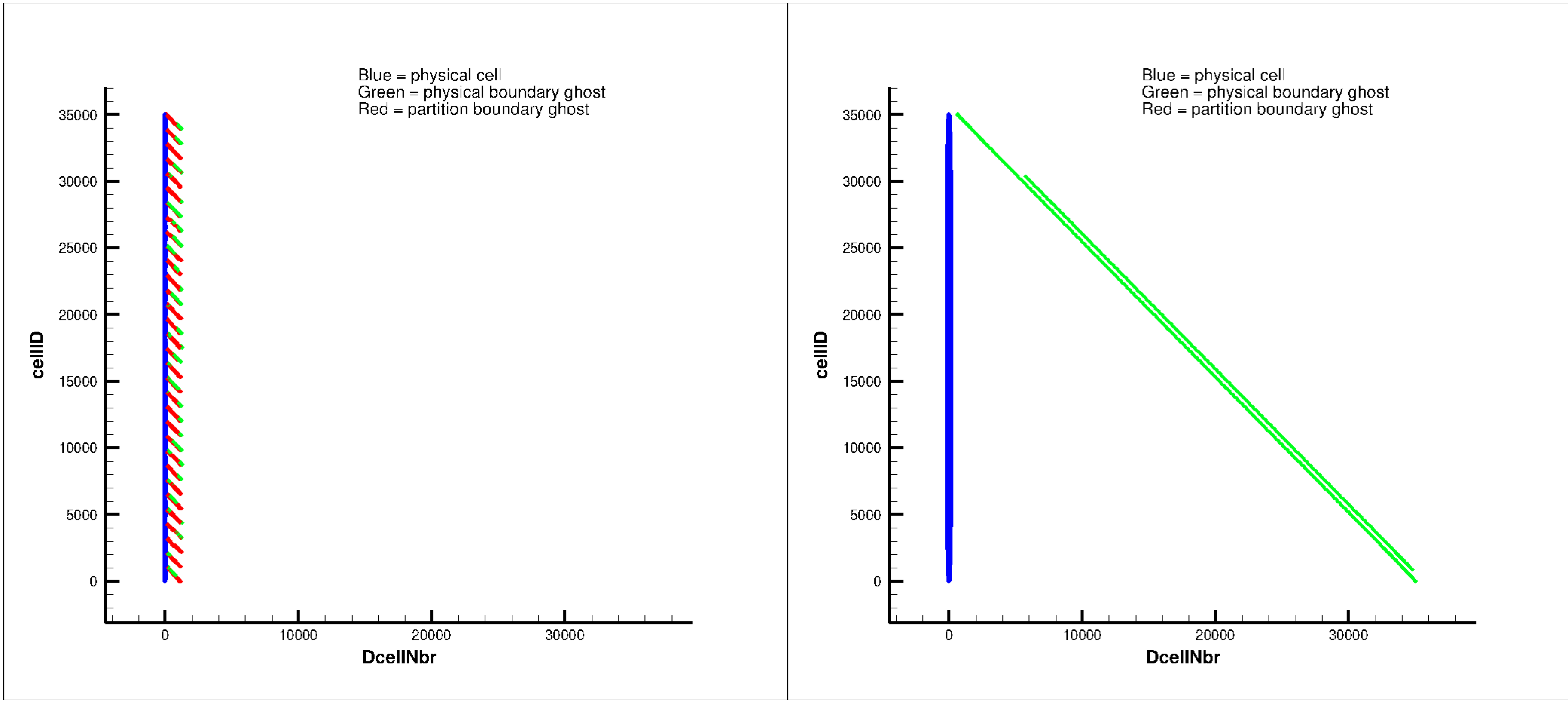
NACA 0012 on 32 processors
Ghost elements packed at end

Blue = physical cell
Red = partition boundary ghost cell
Green = physical boundary ghost cell

Fine-grain Partitioning

Coarse-grain Partitioning

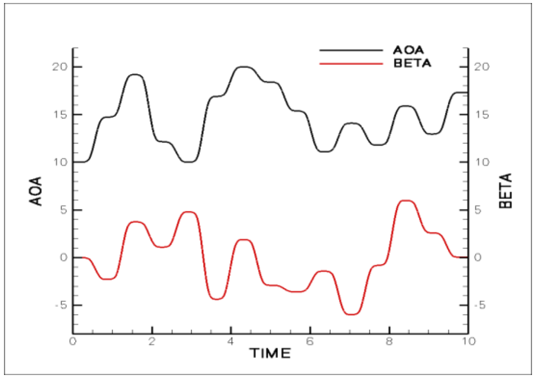
“Cell index in mesh partition”



“Index distance to neighbor cell”

Reduced-Order Modeling

- **Effective use of ROMs necessary for disruptive impact to acquisition programs**



Automated Maneuver Generation to Minimize Parameter Correlation

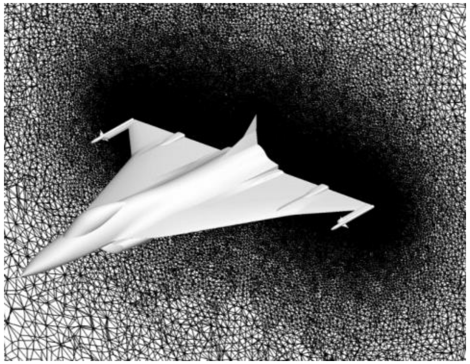
Polyomial (Integrated Loads):

$$C_L = f(\alpha, \beta, p, q, r, \dots)$$

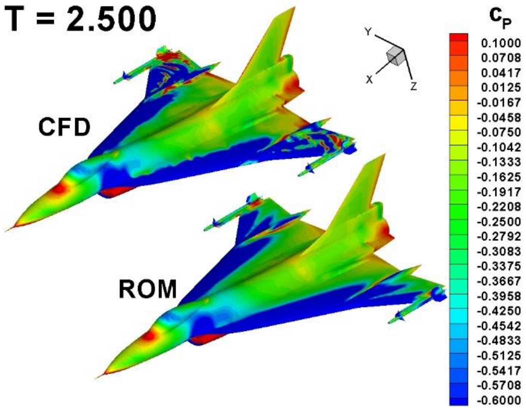
POD-Based (Distributed Loads):

$$q(x,t) = a_n(t)\phi_n(x)$$

ROM Constructed Using On-Design Data



CFD Model



ROM Used For Integrated/Distributed Aero Predictions at Off-Design Conditions

Morton and McDaniel, Thurs @ 1630 in Silver, 325-APA-41 (AIAA 2017-4237)

Summary and Final Thoughts

- Kestrel is a production-quality multidisciplinary simulation tool for fixed-wing air vehicles targeting DoD acquisition professionals
- Kestrel development team must consider usability, robustness, maintainability alongside accuracy
- Three more challenges:
  1. Which models/approaches/techniques do we invest in?
  2. Symbology, coordinate systems, reference frames, etc., across different disciplines creates confusion
  3. Lack of multidisciplinary validation data is debilitating for adoption of multidisciplinary tools

Acknowledgements

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